EXPOSURE APPARATUS HAVING CATADIOPTRIC PROJECTION OPTICAL SYSTEM

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a catadioptric projection optical system suitable for applications to projection optical systems for 1:1 or demagnifying projection in projection exposure apparatus such as steppers used in fabricating, for example, semiconductor devices or liquid crystal display devices, etc., by photolithography process. More particularly, the invention relates to a catadioptric projection optical system of a magnification of 1/4 to 1/5 with a resolution of submicron order in the ultraviolet wavelength region, using a reflecting system as an element in the optical system.

2. Related Background Art

In fabricating semiconductor devices or liquid crystal display devices, etc. by photolithography process, the projection exposure apparatus is used for demagnifying through a projection optical system a pattern image on a reticle (or photomask, etc.) for example at a ratio of about 1/4 to 1/5 to effect exposure of the image on a wafer (or glass plate, etc.) coated with a photoresist or the like.

The projection exposure apparatus with a catadioptric projection optical system is disclosed, for example, in Japanese Laid-open Patent Application No. 2-66510, Japanese Laid-open Patent Application No. 3-282527, U.S. Pat. (USP) No. 5,089,913, Japanese Laid-open Patent Application No. 5-72478, or U.S. Pat. No. 5,052,763, No. 4,779,966, No. 4,65,77, No. 4,701,035.

SUMMARY OF THE INVENTION

An object of the present invention is to provide an exposure apparatus having a catadioptric projection optical system which can use a beam splitting optical system smaller than the conventional polarizing beam splitter and which is excellent in image-forming performance, permitting a sufficiently long optical path of from the concave, reflective mirror to the image plane. Therefore, the catadioptric projection optical system has a space permitting an aperture stop to be set therein, based on a size reduction of the beam splitting optical system such as a polarizing beam splitter. The catadioptric projection optical system can be applied to the projection exposure apparatus of the scanning exposure method, based on use of a compact beam splitting optical system. Besides the projection exposure apparatus of the one-shot exposure method, the catadioptric projection optical system can be also applied to recent apparatus employing a scanning exposure method such as the slit scan method or the step-and-scan method, etc. for effecting exposure while relatively scanning the reticle and the wafer to the projection optical system.

To achieve the above object, as shown in FIG. 1, an exposure apparatus of the present invention comprises at least a wafer stage **3** allowing a photosensitive substrate W to be held on a main surface thereof, an illumination optical system **1** for emitting exposure light of a predetermined wavelength and transferring a predetermined pattern of a mask (reticle R) onto the substrate W, a catadioptric projection optical system **5** provided between a first surface **P1** on which the mask R is disposed and a second surface **P2** to which a surface of the substrate W is corresponded, for projecting an image of the pattern of the mask R onto the substrate W. The illumination optical system 1 includes an

alignment optical system **110** for adjusting a relative positions between the mask R and the wafer W, and the mask R is disposed on a reticle stage **2** which is movable in parallel with respect to the main surface of the wafer stage **3**. The catadioptric projection optical system has a space permitting an aperture stop **6** to be set therein. The sensitive substrate W comprises a wafer **8** such as a silicon wafer or a glass plate, etc., and a photosensitive material **7** such as a photoresist or the like coating a surface of the wafer **8**.

In particular, as shown in FIGS. **2**, **17**, and **31**, the catadioptric projection optical system comprises a first image-forming optical systen $(G_1(f_1), G_2(f_2))$ for forming an intermediate image **11** of the pattern of the mask R, and a second image-forming optical system $(G_3(f_3))$ for forming an image of the intermediate image **11** on the substrate W. The first image-forming optical system has a first group $G_1(f_1)$ with a positive refractive power, comprising a refractive lens component, for converging a light beam from the pattern of the mask R, a second group $G_2(f_2)$ with a positive refractive power, comprising a concave, reflective mirror M_2 for reflecting a light beam from the first group $G_1(f_1)$, for forming the intermediate image **11** of the pattern of the mask R, and a beam splitting optical system **10PBS** (including **10A**, **10B**, and **10C**) or **12** as a beam splitting optical system for changing a traveling direction of one of alight beam from the first group $G_1(f_1)$ and a reflected light from the concave, reflective mirror M_2, and thereby a part of the light beam converged by the second group $G_2(f_2)$ is guided to the second image-forming optical system $G_3(f_3)$. The parameter f_1 means as a focus length of the first group G_1 in the first image-forming optical system, the parameter f_2 means as a focus length of the second group G_2 in the first image-forming optical system, and the parameter f_3 means as a focus length of a lens group G_3 in the second image-forming optical system.

The catadioptric projection optical system in FIG. **2** is an optical system for projecting an image of a pattern of a first surface **P1** onto a second surface **P2**, which has a first image-forming optical system (G_1, G_2) for forming an intermediate image **11** of the pattern of the first surface **P1** and a second image-forming optical system (G_3) for forming an image of the intermediate image **11** on the second surface **P2**.

The first image-forming optical system comprises a first group $G_1(f_1)$ of a positive refractive power, comprising a refractive lens component, for converging a light beam from the pattern of the first surface **P1**, a prism type beam splitter **10PBS** for separating a part of a light beam from the first group by a beam splitter surface **10PBS***a* arranged obliquely to the optical axis **AX1** of the first group, and a second group $G_2(f_2)$ with a positive refractive power, comprising a concave, reflective mirror M_2 for reflecting the light beam separated by the prism type beam splitter **10PBS**, for forming the intermediate image **11** of the pattern near the prism type beam splitter **10PBS**, in which a part of the light beam converged by the second group $G_2(f_2)$ is separated by the prism type beam splitter **10PBS** to be guided to the second image-forming optical system $G_3(f_3)$. The prism type beam splitter is disposed on the optical axis **AX1** of the first group $G_1(f_1)$ and provided between the concave, reflective mirror M_2 and the second image-forming optical system.

In this case, it is desirable that the intermediate image **11** of the pattern be formed inside the prism type beam sputter **10PBS**. Also, as shown in FIG. **2**, it is desired that in order to prevent generation of flare due to repetitive reflections between the concave, reflective mirror M_2 and the second surface **P2**, a polarizing beam sputter be used as the beam

splitter 10PBS and a quarter wave plate 9 be placed between the polarizing beam splitter and the concave, reflective mirror M_2. Further, it is desired that the optical system be telecentric at least on the image plane P2 side.

Next, the catadioptric projection optical system in FIG. 17 is an optical system for projecting an image of a pattern P10 on a first surface P1 onto a second surface P2 which has a first image-forming optical system ($G_1(f_1)$, $G_2(f_2)$) for forming an intermediate image 11 of the pattern P10 of the first surface P1, and a second image-forming optical system ($G_3(f_3)$) for forming an image of the intermediate image 11 on the second surface P2.

The first image-forming optical system comprises a first group $G_1(f_1)$ of a positive refractive power, comprising a refractive lens component, for converging a light beam from the pattern P10 of the first surface P1, a partial mirror 12 for separating a part of the light beam from the first group by a first reflective surface 12*a* arranged obliquely to the optical axis AX1 of the first group, and a second group $G_2(f_2)$ of a positive refractive power, comprising a concave, reflective mirror M_2 for reflecting the light beam of which the part is separated by the partial mirror 12, for forming the intermediate image 11 of the pattern P10 near the partial mirror 12, in which a part of the light beam converged by the second group is guided to the second image-forming optical system $G_3(f_3)$. The partial mirror 12 is positioned so as to avoid being disposed on the optical axis AX1 of the first group and provided between the first group and the second group. The partial mirror 12 further has a second reflective surface for guiding the reflected light beam from the concave, reflective mirror M_2 to the second image-forming optical system, the second reflective surface 12*b* being opposite to the first reflective surface 12*a*.

In this case, because the light beam reflected by a second surface 12*b* of the partial mirror 12 is used, it is desired that an image-forming range be slit or arcuate. Namely, the catadioptric projection optical system in FIG. 17 is suitable for applications to the projection exposure apparatus of the scanning exposure method. In this case, because the use of the partial mirror 12 includes little influence of repetitive reflections, the quarter wave plate can be obviated.

In these arrangements, the following conditions should be preferably satisfied when individual Petzval sums of the first group $G_1(f_1)$, the second group $G_2(f_2)$, and the second image-forming optical system $G_3(f_3)$ are p_1, p_2, p_3 respectively.

$$p_1+p_3>0 \quad (1)$$

$$p_2<0 \quad (2)$$

$$|p_1+p_2+p_3|<0.1 \quad (3)$$

Further, the following conditions should be preferably satisfied when a magnification of primary image formation of from the pattern on the first surface P1 to the intermediate image is β_{12}, a magnification of secondary image formation of from the intermediate image to the image on the second surface P2 is β_3, and a magnification of from the first surface to the second surface is β.

$$0.1<|\beta_{12}|<0.5 \quad (4)$$

$$0.25<|\beta_3|<2 \quad (5)$$

$$0.1<|\beta|<0.5 \quad (6)$$

The catadioptric projection optical system in FIG. 2 is suitably applicable to the projection exposure apparatus of

the one-shot exposure method. In this case, because the prism type beam splitter **10PBS** is used to separate the light beam coming from the concave, reflective mirror M_2 from the light beam going to the concave, reflective mirror M_2 and because the beam splitter **10PBS** is located near the portion where the light beam from the concave, reflective mirror M_2 is once converged to be focused, the prism type beam splitter **10PBS** can be constructed in a reduced scale. In other words, in the catadioptric projection optical system, since an intermediate image **11** of the pattern of the first surface **P1** is formed between the concave, reflective mirror M_2 and the second image-forming optical system, the diameter of the light beam traveling from the concave, reflective mirror M_2 to the beam splitter **10PBS** will become small.

Also, because the image is once formed between the concave reflective mirror M_2 and the image plane **P2**, an aperture stop **6** can be placed in the second image-forming optical system $G_3(f_3)$. Accordingly, a coherence factor (σ value) can be readily controlled. With regard to this, because after the primary image formation, the secondary image formation is made by the second image-forming optical system $G_3(f_3)$, the working distance between a fore end lens in the second image-forming optical system $G_3(f_3)$ and the image plane P2 can be secured sufficiently long. In particular, because the projection exposure apparatus of the one-shot exposure method employs the beam splitter **10PBS** located near the plane of primary image formation, the beam splitter **10PBS** can be made as small as possible.

Next, because the catadioptric projection optical system in FIG. **17** uses the partial mirror **12**, a best image region on the image plane **P2** is slit or arcuate, thus being suitable for applications to the projection exposure apparatus of the scanning exposure method. In this case, because the image is once formed near the partial mirror **12**, the partial mirror **12** may be small in size and characteristics of a reflective film of the partial mirror **12** are stable.

Also, the optical path can be separated simply by providing the partial mirror **12** with a small angle of view. Namely, because a large angle of view is unnecessary for separation of the optical path, a sufficient margin is left in the image-forming performance. With regard to this, ordinary catadioptric projection optical systems need a maximum angle of view of about 20° or more for separation of the optical path, while an angle of view of the light beam entering the partial mirror **12** is about 10°, which is easy in aberration correction.

A so-called ring field optical system is known as a projection optical system for the scanning exposure method, and the ring field optical system is constructed to illuminate only an off-axis annular portion. It is, however, difficult for the ring field optical system to have a large numerical aperture, because it uses an off-axis beam. Further, because optical members in that system are not symmetric with respect to the optical axis, processing, inspection, and adjustment of the optical members are difficult, and accuracy control or accuracy maintenance is also difficult. In contrast with it, because the angle of view is not large in the present invention, the optical system is constructed in a structure with less eclipse of beam.

Since the first image-forming optical system ($G_1(f_1)$, $G_2(f_2)$) and the second image-forming optical system $G_3(f_3)$ are constructed independently of each other, the optical system is easy in processing, inspection, and adjustment of optical members, is easy in accuracy control and accuracy maintenance, and has excellent image-forming characteristics to realize a large numerical aperture.

Next, in the catadioptric projection optical system shown in FIG. 2 or 17, a Petzval sum of the entire optical system

first needs to be set as close to 0, in order to further improve the performance of optical system. Therefore, conditions of equations (1) to (3) should be preferably satisfied.

Satisfying the conditions of equations (1) to (3) prevents curvature of the image plane in the optical performance, which thus makes flatness of the image plane excellent. Above the upper limit of the condition of equation (3) (or if $p_1+p_2+p_3>0.1$), the image plane is curved as concave to the object plane; below the lower limit of the condition of equation (3) (or if $p_1+p_2+p_3<-0.1$), the image plane is curved as convex to the object, thereby considerably degrading the image-forming performance.

When the conditions of equations (4) to (6) are satisfied as to the magnification β_{12} of primary image formation, the magnification β_3 of secondary image formation, and the magnification β of overall image formation, the optical system can be constructed without difficulties. Below the lower limit of each condition of equation (4) to (6), the demagnifying ratio becomes excessive, which makes wide-range exposure difficult. Above the upper limit, the demagnifying ratio becomes closer to magnifying ratios, which is against the original purpose of use for reduction projection in applications to the projection exposure apparatus.

In this case, because the condition of equation (4) is satisfied, the most part of the demagnifying ratio of the overall optical system relies on the first image-forming optical system. Accordingly, the beam splitter **10PBS** or the partial mirror **12** can be constructed in a small scale in particular. If the position of the beam splitter **10PBS** in FIG. **2** or the partial mirror **12** in FIG. **6** as beam splitting means is made nearly coincident with the entrance pupil and the exit pupil of optical system, a shield portion on the pupil does not change against a change of object height, and therefore, no change of image-forming performance appears across the entire image plane.

Also, it is desired that such an optical system for exposure be telecentric at least on the image plane side in order to suppress a change of magnification against variations in the direction of the optical axis, of the image plane where the wafer or the like is located.

The present invention will become more fully understood from the detailed description given hereinbelow and the accompanying drawings which are given by way of illustration only, and thus are not to be considered as limiting the present invention.

Further scope of applicability of the present invention will become apparent from the detailed description given hereinafter. However, it should be understood that the detailed description and specific examples, while indicating preferred embodiments of the invention, are given by way of illustration only, since various changes and modifications within the spirit and scope of the invention will become apparent to those skilled in the art form this detailed description.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a structural drawing to show the basic structure of the exposure apparatus according to the present invention.

FIG. **2** is a structural drawing to show the basic structure of the catadioptric projection optical system **5** in FIG. **1**.

FIG. **3** is an illustration of optical paths of a light beam traveling in the catadioptric projection optical system in FIG. **2**.

FIG. **4** is an optical path development of a first embodiment of the catadioptric projection optical system in FIG. **2**, the optical path comprising the optical paths OP1, OP2, OP3 shown in FIG. **3**.

FIGS. 5 to 9 are aberration diagrams of the first embodiment.

FIG. 10 is an optical path development of the projection optical system in the second embodiment.

FIGS. 11 to 16 are aberration diagrams of the second embodiment.

FIG. 17 is a structural drawing to show the basic structure of the projection optical system in the third embodiment.

FIG. 18 is an optical path development of the projection optical system in the third embodiment.

FIGS. 19 to 24 are aberration diagrams of the third embodiment.

FIG. 25 is an optical path development of the projection optical system in the fourth embodiment.

FIGS. 26 to 30 are aberration diagrams of the fourth embodiment.

FIG. 31 is a structural drawing to show a structure of the catadioptric projection optical system applied to a common exposure apparatus.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Various embodiments of the catadioptric projection optical system according to the present invention will be described with reference to the drawings. In the examples, the present invention is applied to the projection optical system in the projection exposure apparatus for projecting an image of patterns of reticle onto a wafer coated with a photoresist. FIG. 1 shows a basic structure of the exposure apparatus according to the present invention. As shown in FIG. 1, an exposure apparatus of the present invention comprises at least a wafer stage 3 allowing a photosensitive substrate W to be held on a main surface 3*a* thereof, an illumination optical system 1 for emitting exposure light of a predetermined wavelength and transferring a predetermined pattern of a mask (reticle R) onto the substrate W, a light source 100 for supplying an exposure light to the illumination optical system 1, a catadioptric projection optical system 5 provided between a first surface P1 (object plane) on which the mask R is disposed and a second surface P2 (image plane) to which a surface of the substrate W is corresponded, for projecting an image of the pattern of the mask R onto the substrate W. The illumination optical system 1 includes an alignment optical system 110 for adjusting a relative positions between the mask R and the wafer W, and the mask R is disposed on a reticle stage 2 which is movable in parallel with respect to the main surface of the wafer stage 3. A reticle exchange system 200 conveys and changes a reticle (mask R) to be set on the reticle stage 2. The reticle exchange system 200 includes a stage driver for moving the reticle stage 2 in parallel with respect to the main surface 3*a* of the wafer stage 3. The catadioptric projection optical system 5 has a space permitting an aperture stop 6 to be set therein. The sensitive substrate W comprises a wafer 8 such as a silicon wafer or a glass plate, etc., and a photosensitive material 7 such as a photoresist or the like coating a surface of the wafer 8. The wafer stage 3 is moved in parallel with respect to a object plane P1 by a stage control system 300. Further, since a main control section 400 such as a computer system controls the light source 100, the reticle exchange system 200, the stage control system 300 or the like, the exposure apparatus can perform a harmonious action as a whole.

The techniques relating to an exposure apparatus of the present invention are described, for example, in U.S. patent

applications Ser. No. 255,927, No. 260,398, No. 299,305, U.S. Pat. No. 4,497,015, No. 4,666,273, No. 5,194,893, No. 5,253,110, No. 5,333,035, No. 5,365,051, No. 5,379,091, or the like. The reference of U.S. patent application Ser. No. 255,927 teaches an illumination optical system (using a laser source) applied to a scan type exposure apparatus. The reference of U.S. patent application Ser. No. 260,398 teaches an illumination optical system (using a lamp source) applied to a scan type exposure apparatus. The reference of U.S. patent application Ser. No. 299,305 teaches an alignment optical system applied to a scan type exposure apparatus. The reference of U.S. Pat. No. 4,497,015 teaches an illumination optical system (using a lamp source) applied to a scan type exposure apparatus. The reference of U.S. Pat. No. 4,666,273 teaches a step-and repeat type exposure apparatus capable of using the catadioptric projection optical system of the present invention. The reference of U.S. Pat. No. 5,194,893 teaches an illumination optical system, an illumination region, mask-side and reticle-side interferometers, a focusing optical system, alignment optical system, or the like. The reference of U.S. Pat. No. 5,253,110 teaches an illumination optical system (using a laser source) applied to a step-and-repeat type exposure apparatus. The '110 reference can be applied to a scan type exposure apparatus. The reference of U.S. Pat. No. 5,333,035 teaches an application of an illumination optical system applied to an exposure apparatus. The reference of U.S. Pat. No. 5,365,051 teaches a auto-focusing system applied to an exposure apparatus. The reference of U.S. Pat. No. 5,379,091 teaches an illumination optical system (using a laser source) applied to a scan type exposure apparatus.

In each embodiment as described below, a lens arrangement is illustrated as an optical path development, for example as shown in FIG. **4**. In each optical path development, a reflective surface is shown as a transmissive surface, and optical elements are arranged in the order in which light from a reticle R passes. Also, a virtual plane of flat surface (for example r_{10}) is used at a reflective surface of a concave, reflective mirror (for example r_{14}). In order to indicate a shape and separation of lens, for example as shown in FIG. **4**, the pattern surface of reticle R is defined as the zeroth surface, surfaces that the light emergent from the reticle R passes in order before reaching the wafer W are defined as i-th surfaces (i=1, 2, . . .), and the sign for radii r_i of curvature of the i-th surfaces is determined as positive if a surface is convex to the reticle **10** in the optical path development. A surface separation between the i-th surface and the (i+1)-th surface is defined as d_i. SiO_2 as a glass material means silica glass. A refractive index of silica glass for reference wavelength (193 nm) used is as follows.

silica glass: 1.56100

First Embodiment

The first embodiment is a projection optical system with a magnification of 1/4x, suitably applicable to the projection exposure apparatus of the one-shot exposure method (steppers etc.). This first embodiment is an embodiment corresponding to the optical system of FIG. **2** as well. FIG. **4** is an optical path development of the projection optical system of the first embodiment. As shown in FIG. **4**, light from the patterns on the reticle R travels through a first converging group G_1 consisting of four refractive lenses and then is reflected by a beam splitter surface ($r_{ }$) in a cubic polarizing beam splitter **10A**. An optical path of the light is corresponded to the optical path OP1 in FIG. **3**. The reflected light passes through a quarter wave plate **9** (not shown in FIG. **4**) to reach a second converging group G_2 consisting of

a negative meniscus lens L_{21} and a concave, reflective mirror M_2. The light reflected by the second converging group G_2 passes through the quarter wave plate (not shown in FIG. **4**) to form an intermediate image of the patterns in the polarizing beam splitter **10A** (see optical paths OP**2** and OP**3** in FIG. **4**).

Then, light from the intermediate image, that is, a light beam having passed through the polarizing beam splitter **10A**, then passes through a third converging group G_3 consisting of fourteen refractive lenses to form a second intermediate image of the patterns on the surface of wafer W. In this case, an aperture stop **6** is placed on a Fourier transform plane in the third converging group G_3, i.e., between a positive meniscus lens L_{36} and a concave lens L_{37}.

Also, as shown in FIG. **4**, the first converging group G_1 is composed of, in the order from the reticle R side, a positive meniscus lens L_{11} with a convex surface to the reticle R, a negative meniscus lens L_{12} with a convex surface to the reticle R, a double convex lens (hereinafter referred to simply as "convex lens") L_{13}, and a double concave lens (hereinafter referred to simply as "concave lens") L_{14}, and the second converging group G_2 is composed of a negative meniscus lens L_{21} with a concave surface to the reticle R and a concave, reflective mirror M_2. Further, the third converging group G_3 is composed of a positive meniscus lens L_{31} with a concave surface to the reticle R, a convex lens L_{32}, a positive meniscus lens L_{33} with a concave surface to the reticle R, a convex lens L_{34}, a convex lens L_{35}, a positive meniscus lens L_{36} with a convex surface to the reticle R, a concave lens L_{37}, a convex lens L_{38}, a convex lens L_{39}, a negative meniscus lens L_{310} with a concave surface to the reticle R, a convex lens L_{311}, a negative meniscus lens L_{312} with a convex surface to the reticle R, a positive meniscus lens L_{313} with a convex surface to the reticle R, and a negative meniscus lens L_{314} with a convex surface to the reticle R.

A magnification of the total system is 1/4× (demagnification), a numerical aperture NA on the wafer W side (image side) is 0.4, and the object height is 30 mm.

The refractive lenses all are made of a kind of optical glass of fused quartz, which are corrected for axial and lateral chromatic aberrations for a wavelength band of 1 nm at the wavelength of 193 nm of the ultraviolet excimer laser light. Also, the optical system has excellent image-forming performance, as well corrected for spherical aberration, coma, astigmatism, and distortion up to a nearly zero aberration state, and the good image-forming performance can be retained even if the optical system of FIG. **4** is proportionally enlarged two to three times.

Next Table 1 shows radii of curvature r_i, surface separations d_i, and glass materials in the first embodiment of FIG. **4**. In the following table, the fifteenth surface is a virtual plane for indicating the concave, reflective mirror in the optical path development.

TABLE 1

i	r_i	d_i	Glass Material	i	r_i	d_i	Glass Material
0	--	2.2		24	-146.60	6.0	S_iO_2
1	45.87	15.0	S_iO_2	25	-82.20	1.0	
2	321.75	7.5		26	146.40	9.4	S_iO_2
3	4161.48	6.0	S_iO_2	27	-114.12	32.9	
4	86.56	11.7		28	84.83	[illegible]	S_iO_2
5	243.98	[illegible]	S_iO_2	29	-182.36	[illegible]	

TABLE 1-continued

i	r_i	d_i	Glass Material	i	r_i	d_i	Glass Material
6	[illegible]	[illegible]		30	[illegible]	[illegible]	SiO_2
7	[illegible]	[illegible]	SiO_2	31	[illegible]	[illegible]	
8	[illegible]	[illegible]		32	−48.51	5.6	SiO_2
9	∞	[illegible]	SiO_2	33	[illegible]	4.3	
10	∞	52.6		34	[illegible]	8.2	SiO_2
11	∞	[illegible]		35	[illegible]	[illegible]	
12	[illegible]	[illegible]	SiO_2	36	[illegible]	8.2	SiO_2
13	140.44	4.1		37	61.92	3.7	
14	[illegible]	[illegible]		38	−38.44	6.7	SiO_2
15	∞	4.1		39	[illegible]	[illegible]	
16	140.44	[illegible]	SiO_2	40	[illegible]	[illegible]	SiO_2
17	[illegible]	79.6		41	[illegible]	[illegible]	
18	∞	30.0	SiO_2	42	[illegible]	5.7	SiO_2
19	∞	5.0		43	16.97	2.5	
20	−41.51	[illegible]	SiO_2	44	[illegible]	[illegible]	SiO_2
21	[illegible]	[illegible]		45	[illegible]	0.5	
22	244.39	[illegible]	SiO_2	46	208.17	3.7	SiO_2
23	−64.38	1.0		47	39.10	7.0	

Also, FIG. **5** to **7** show longitudinal aberration diagrams of the first embodiment, FIG. **8** shows a lateral chromatic aberration diagram of the first embodiment, and FIG. **9** shows transverse aberration diagrams of the first embodiment. In particular, FIG. **5** shows spherical aberration of the first embodiment, FIG. **6** shows astigmatism of the first embodiment, and FIG. **7** shows distortion of the first embodiment. In these aberration diagrams, symbols J, P, and Q represent respective characteristics when the used wavelength is changed in a selected range with respect to the reference wavelength. It is seen from these aberration diagrams that though the numerical aperture is large, 0.4, in this example, the aberrations are well corrected in a wide image circle region. Further, chromatic aberration is well corrected as well.

Second Embodiment

The second embodiment is a projection optical system with a magnification of 1/4x, suitably applicable to the projection exposure apparatus of the scanning exposure method. This second embodiment is an embodiment as a modification of the optical system of FIG. **2** as well. FIG. **10** is an optical path development of the projection optical system of the present embodiment, and FIG. **11** shows an illumination area on the reticle R. As shown in this FIG. **11**, an arcuate illumination area **P10** on the reticle R is illuminated by an illumination optical system not shown. Then, in FIG. **10**, light from patterns in the illumination area **P10** on the reticle R travels through a first converging group G_1 consisting of four refractive lenses, and then passes a transmissive part of a junction surface in a cubic, partially-reflective, beam splitter **10B**. A reflective film **10B***a* with a reflectivity of approximately 100% is formed in a peripheral part of the junction surface of the partially-reflective beam splitter **10B**, and a portion other than this reflective film **10B***a* is a transmissive surface with a transmittance of approximately 100%.

The reflected light reaches a second converging group G_2 consisting of a negative meniscus lens L_{2} and a concave, reflective mirror M_2, and light reflected by the second converging group G_2 forms an intermediate image of the patterns in the illumination area **P10**, near the reflective film **10B***a* in the partially-reflective beam splitter **10B**. Then light from the intermediate image is reflected by the reflective film 10Ba, then passes through a third converging group G_3 consisting of fourteen refractive lenses, and forms a second

intermediate image of the patterns on the surface of wafer W. Letting β be a projection magnification of from reticle R to wafer W, the reticle area R is scanned upward at a predetermined velocity V_R and in synchronization therewith the wafer W is scanned upward at a velocity $\beta \cdot V_R$, thus carrying out exposure in the scanning exposure method.

Also, as shown in FIG. **10**, the first converging group G_1 is composed of, in the order from the reticle R side, a convex lens L_{11}, a concave lens L_{12}, a positive meniscus lens L_{13} with a concave surface to the reticle R, and a concave lens L_{14}, and the second converging group G_2 is composed of a negative meniscus lens L_{21} with a concave surface to the reticle R and a concave, reflective mirror M_2. Further, the third converging group G_3 is composed of a positive meniscus lens L_{31} with a concave surface to the reticle R, a convex lens L_{32}, a positive meniscus lens L_{33} with a concave surface to the reticle R, a convex lens L_{34}, a convex lens L_{35}, a positive meniscus lens L_{36} with a convex surface to the reticle R, a concave lens L_{37}, a positive meniscus lens L_{38} with a concave surface to the reticle **10**, a convex lens L_{39}, a negative meniscus lens L_{310} with a concave surface to the reticle R, a convex lens L_{311}, a negative meniscus lens L_{312} with a convex surface to the reticle R, a positive meniscus lens L_{313} with a convex surface to the reticle R, and a negative meniscus lens L_{314} with a convex surface to the reticle R.

A magnification of the total system is 1/4x (demagnification), a numerical aperture NA on the wafer W side (image side) is 0.5, and the object height is 22 mm. The optical system may be used in the one-shot exposure method.

The refractive lenses all are made of a kind of optical glass of fused quartz, which are corrected for axial and lateral chromatic aberrations for a wavelength band of 1 nm at the wavelength of 193 nm of the ultraviolet excimer laser light. Also, the optical system has excellent image-forming performance, as well corrected for spherical aberration, coma, astigmatism and distortion up to a nearly zero aberration state.

Next Table 2 shows radii of curvature ri, surface separations di, and glass materials in the second embodiment of FIG. **10**. In the following table, the fourteenth surface is a virtual plane for indicating the concave, reflective mirror in the optical path development.

TABLE 2

i	r_i	d_i	Glass Material	i	r_i	d_i	Material
0	—	2.2		24	−75.11	1.3	
1	45.65	10.0	S_iO_2	25	319.62	9.4	S_iO_2
2	−183.72	12.0		26	−119.09	32.9	
3	−91.37	6.3	S_iO_2	27	56.25	6.1	S_iO_2
4	47.58	11.7		28	−120.67	1.0	
5	−221.29	10.0	S_iO_2	29	49.04	6.0	S_iO_2
6	−98.98	7.3		30	99.71	4.0	
7	110.83	6.1	S_iO_2	31	48.51	5.6	S_iO_2
8	66.11	3.0		32	54.15	4.3	
9	∞	40.0	S_iO_2	33	−361.48	8.2	S_iO_2
10	∞	77.7		34	−69.92	1.3	
11	−78.96	7.2	S_iO_2	35	148.52	8.2	S_iO_2
12	−145.84	4.3		36	−71.54	3.7	
13	−92.74	[illegible]		37	−37.19	6.7	S_iO_2
14	∞	4.3		38	−41.33	1.0	
15	145.54	7.2	S_iO_2	39	194.05	8.0	S_iO_2
16	78.96	77.7		40	−62.51	1.0	
17	∞	40.0	S_iO_2	41	17.77	5.7	S_iO_2
18	∞	[illegible]		42	13.88	2.5	
19	−40.58	6.3	S_iO_2	43	17.52	8.0	S_iO_2

TABLE 2-continued

i	r_i	d_i	Glass Material	i	r_i	d_i	Material
20	−36.69	1.0		44	93.95	0.5	
21	212.61	10.0	S_iO_2	45	98.19	3.7	S_iO_2
22	−65.47	1.0		46	31.30	7.0	
23	−134.41	6.0	S_iO_2				

Also, FIG. **12** to **14** show longitudinal aberration diagrams of the second embodiment, FIG. **15** shows a lateral chromatic aberration diagram of the second embodiment, and FIG. **16** shows transverse aberration diagrams of the second embodiment. In particular, FIG. **12** shows spherical aberration of the second embodiment, FIG. **13** shows astigmatism of the second embodiment, and FIG. **14** shows distortion of the second embodiment. It is seen from these aberration diagrams that although the numerical aperture is large as 0.5 in this example, the aberrations are well corrected in a wide image circle region. Further, chromatic aberration is well corrected as well.

Third Embodiment

The third embodiment is a projection optical system with a magnification of 1/4x, suitably applicable to the projection exposure apparatus of the scanning exposure method. This third embodiment is an embodiment of the optical system using a partial mirror as well. As shown in FIG. **17**, the partial mirror **12** is provided between the first converging group G_1 and the second converging group G_2, and positioned so as to avoid being disposed on the optical axes **AX1**, **AX2** of the first converging group G_1 and the third converging group G_3. The partial mirror **12** has a first reflective surface **12***a* arranged obliquely to the optical axis **AX1** of the first converging group G_1 and a second reflective surface **12***b* opposite to the first reflective surface **12***a*.

FIG. **18** is an optical path development of the projection optical system of the third embodiment, and FIG. **19** shows an illumination region **P10** on the reticle R. As shown in this FIG. **19**, an arcuate illumination area **P10** on the reticle R is illuminated by an illumination optical system **1**. Then, in FIG. **18**, light from patterns in the illumination area **P10** on the reticle R travels through a first converging group G_1 consisting of four refractive lenses and then passes beside the partial mirror **12**. In other words, the first reflective surface **12***a* of the partial mirror **12** separates a part of the light from the first converging group G_1.

This passing light reaches a second converging group G_2 consisting of a negative meniscus lens L_{2} and a concave, reflective mirror M_2, and light reflected by the second converging group G_2 forms an intermediate image **11** of the patterns in the illumination area **P10**, near the partial mirror **12** (see FIG. **17**). Then light from the intermediate image **11** is reflected by a second reflective surface **12***b* of the partial mirror **12** and thereafter passes through a third converging group G_3 consisting of fourteen refractive lenses to form a second intermediate image of the patterns on the surface of wafer W. Also, an aperture stop **6** is placed on a Fourier transform plane in the third converging group G_3, i.e., between a convex lens L_{34} and a convex lens L.S. In this case, letting β be a projection magnification of from reticle R to wafer W, the reticle area R is scanned upward at a predetermined velocity V_R and in synchronization therewith the wafer **11** is scanned upward at a velocity ($\beta \cdot V_R$, thus performing exposure in the scanning exposure method.

Also, as shown in FIG. **18**, the first converging group G_1 is composed of, in the order from the reticle R side, a positive meniscus lens L_{11} with a convex surface to the

reticle R, a negative meniscus lens L_{12} with a convex surface to the reticle R, a convex lens L_{13} and a concave lens L_{14}, and the second converging group G_2 is composed of a negative meniscus lens L_{21} with a concave surface to the reticle R, and a concave, reflective mirror M_2. Further, the third converging group G_3 is composed of a negative meniscus lens L_{31} with a concave surface to the reticle R, a positive meniscus lens L_{32} with a concave surface to the reticle R, a positive meniscus lens L_{33} with a concave surface to the reticle R, a convex lens L_{34}, a convex lens L_{35}, a positive meniscus lens L_{36} with a convex surface to the reticle R, a concave lens L_{37}, a positive meniscus lens L_{38} with a concave surface to the reticle R, a convex lens L_{39}, a negative meniscus lens L_{3X} with a concave surface to the reticle R, a convex lens L_{40}, a negative meniscus lens L_{41} with a convex surface to the reticle R, a positive meniscus lens L_{42} with a convex surface to the reticle R, and a negative meniscus lens L_{43} with a convex surface to the reticle R.

A magnification of the total system is 1/4x (demagnification), a numerical aperture NA on the wafer 11 side (image side) is 0.4, and the object height is 26 mm. The optical system may be used in the one-shot exposure method.

The refractive lenses all are made of a kind of optical glass of fused quartz, which are corrected for axial and lateral chromatic aberrations for a wavelength band of 1 nm at the wavelength of 193 nm of the ultraviolet excimer laser light. Also, the optical system has excellent image-forming performance, as well corrected for spherical aberration, coma, astigmatism, and distortion up to a nearly zero aberration state, and the good image-forming performance can be retained even if the optical system is proportionally enlarged two to three times.

Next Table 3 shows radii of curvature r_i, surface separations d_i and glass materials in the third embodiment of FIGS. **17** and **18**. In the following table, the fourteenth surface is a virtual plane for indicating the concave, reflective mirror in the optical path development.

TABLE 3

i	r_i	d_i	Glass Material	i	r_i	d_i	Material
0	[illegible]	2.2		24	140.91	9.4	S_iO_2
1	38.17	[illegible]	S_iO_2	25	−191.84	[illegible]	
2	76.72	12.0		26	92.51	[illegible]	S_iO_2
3	[illegible]	[illegible]	S_iO_2	27	[illegible]	[illegible]	
4	30.99	11.7		28	58.31	7.0	S_iO_2
5	36.73	[illegible]	S_iO_2	29	427.83	4.0	
6	−337.52	6.5		30	−43.79	4.0	S_iO_2
7	[illegible]	[illegible]	S_iO_2	31	[illegible]	[illegible]	
8	[illegible]	54.5		32	−48.72	8.2	S_iO_2
9	∞	30.3		33	−43.49	0.3	
10	∞	69.6		34	165.95	8.2	S_iO_2
11	−87.27	8.0	S_iO_2	35	−82.87	3.7	
12	[illegible]	4.8		36	[illegible]	6.7	S_iO_2
13	[illegible]	[illegible]		37	[illegible]	[illegible]	
14	∞	4.8		38	75.16	[illegible]	S_iO_2
15	[illegible]	[illegible]	S_iO_2	39	−168.78	[illegible]	
16	[illegible]	[illegible]		40	21.81	[illegible]	S_iO_2
17	∞	14.6		41	[illegible]	[illegible]	
18	[illegible]	[illegible]	S_iO_2	42	[illegible]	[illegible]	S_iO_2
19	[illegible]	[illegible]		43	[illegible]	[illegible]	
20	[illegible]	[illegible]	S_iO_2	44	[illegible]	3.7	S_iO_2
21	−39.93	1.0		45	13.10	6.9	
22	−280.59	8.0	S_iO_2				
23	−108.42	1.0					

Also, FIG. **20** to **22** show longitudinal aberration diagrams of the third embodiment, FIG. **23** shows a lateral chromatic aberration diagram of the third embodiment, and FIG. **24** shows transverse aberration diagrams of the third

embodiment. In particular, FIG. **20** shows spherical aberration of the third embodiment. FIG. **21** shows astigmatism of the third embodiment, and FIG. **22** shows distortion of the third embodiment. It is seen from these aberration diagrams that although the numerical aperture is large as 0.4 in this example, the aberrations are well corrected in a wide image circle region. Further, chromatic aberration is well corrected as well.

Fourth Embodiment

The fourth embodiment is a projection optical system with a magnification of 1/4x, suitably applicable to the projection exposure apparatus of the one-shot exposure method (steppers etc.). This fourth embodiment is an embodiment as a modification of the optical system of FIG. **2** as well. FIG. **25** is an optical path development of the projection optical system of the fourth embodiment. As shown in FIG. **25**, light from patterns on the reticle R travels through a first converging group G_1 consisting of four refractive lenses and then enters a beam splitter surface **10C***a* in a polarizing beam splitter **10C** of a rectangular parallelepiped. The polarizing beam splitter **10C** in the present embodiment is of a rectangular parallelepiped, and an incident surface (r_c) of the illumination light is wider by a region **13** than a projection image of the beam splitter surface **10C***a*. This permits the polarizing beam splitter **10C** in FIG. **25** to be constructed thinner than the polarizing beam splitter **10A** in FIG. **4**.

A light beam having passed through the beam splitter surface **10C***a* passes through a quarter wave plate **9** (not shown in FIG. **25**) to reach a second converging group G_2 consisting of a negative meniscus lens L_{20} and a concave, reflective mirror M_2, and light reflected by the second converging group G_2 travels through the quarter wave plate **9** (not shown FIG. **25**), then is reflected by the beam splitter surface **10C***a* in the polarizing beam splitter **10C**, and forms an intermediate image **11** of the patterns at a position in the vicinity of the polarizing beam splitter **10C**.

Then a light beam from the intermediate image **11** passes through a third converging group G_3 consisting of fourteen refractive lenses to form a second intermediate image of the patterns on the surface of wafer W. In this case, an aperture stop **6** is placed on a Fourier transform plane in the third converging group G_3, that is, between a positive meniscus lens Lag and a convex lens L_{3}.

Also, as shown in FIG. **25**, the first converging group G_1 is composed of, in the order from the reticle R side, a positive meniscus lens L_{11} with a convex surface to the reticle R, a concave lens L_{12}, a convex lens L_{13}, and a concave lens L_{14}, and the second converging group G_2 is composed of a negative meniscus lens Leo with a concave surface to the reticle R, and a concave, reflective mirror M_2. Further, the third converging group G_3 is composed of a positive meniscus lens L_{31} with a concave surface to the reticle R, a convex lens L_{32}, a negative meniscus lens L_{33} with a concave surface to the reticle R, a convex lens L_{34}, a convex lens L_{35}, a positive meniscus lens L_{36} with a convex surface to the reticle R, a concave lens L_{37}, a positive meniscus lens L_{38} with a concave surface to the reticle R, a convex lens L_{39}, a negative meniscus lens L_{3X} with a concave surface to the reticle R, a convex lens L_{3H}, a negative meniscus lens L_{3} with a convex surface to the reticle R, a positive meniscus lens L_{3} with a convex surface to the reticle R, and a negative meniscus lens L_{3} with a convex surface to the reticle R.

A magnification of the total system is 1/4x (demagnification), a numerical aperture NA on the wafer **11** side (image side) is 0.6, and the object height is 20 mm.

The refractive lenses all are made of a kind of optical glass of fused quartz, which are corrected for axial and

lateral chromatic aberrations for a wavelength band of 1 nm at the wavelength of 193 nm of the ultraviolet excimer laser light. Also, the optical system has excellent image-forming performance, as well corrected for spherical aberration, coma, astigmatism, and distortion up to a nearly zero aberration state, and the good image-forming performance can be retained even if the optical system of FIG. **25** is proportionally enlarged two to three times.

Next Table 4 shows radii of curvature r_i, surface separations d_i and glass materials in the fourth embodiment of FIG. **25**. In the following table, the fourteenth surface is a virtual plane for indicating the concave, reflective mirror in the optical path development.

TABLE 4

i	r	d_i	Glass Material	i	r_i	d_i	Material
0	∞	2.2		24	−95.92	1.0	
1	48.62	[illegible]	S_iO_2	25	426.51	8.4	S_iO_2
2	319.17	12.6		26	−155.92	32.9	
3	−250.41	6.0	S_iO_2	27	65.87	7.0	S_iO_2
4	42.75	11.7		28	−861.00	1.0	
5	1371.37	10.0	S_iO_2	29	45.43	6.0	S_iO_2
6	−83.00	7.3		30	144.51	6.0	
7	−46.47	6.0	S_iO_2	31	−47.72	3.6	S_iO_2
8	73.09	5.0		32	69.88	4.3	
9	∞	40.0	S_iO_2	33	−139.82	6.2	S_iO_2
10	∞	[illegible]		34	[illegible]	3.3	
11	−78.86	7.2	S_iO_2	35	[illegible]	7.2	S_iO_2
12	−145.84	4.3		36	−61.66	3.7	
13	−92.70	1.0		37	−35.40	6.7	S_iO_2
14	∞	4.3		38	−42.77	1.0	
15	145.84	7.2	S_iO_2	39	194.25	8.0	S_iO_2
16	78.96	60.7		40	−64.00	1.0	
17	∞	40.0	S_iO_2	41	21.24	5.7	S_iO_2
18	∞	40.0		42	16.45	1.5	
19	−48.19	6.0	S_iO_2	43	17.66	9.0	S_iO_2
20	−39.43	1.0		44	[illegible]	0.5	
21	99.65	10.0	S_iO_2	45	60.80	3.7	S_iO_2
22	−69.37	1.0		46	40.36		
23	−82.13	6.0	S_iO_2				

Also, FIG. **26** to **28** show longitudinal aberration diagrams of the fourth embodiment, FIG. **29** shows a lateral chromatic aberration diagram of the fourth embodiment, and FIG. **30** shows transverse aberration diagrams of the fourth embodiment. In particular, FIG. **26** shows spherical aberration of the fourth embodiment, FIG. **27** shows astigmatism of the fourth embodiment, and FIG. **28** shows distortion of the fourth embodiment. It is seen from these aberration diagrams that although the numerical aperture is large as 0.6 in this example, the aberrations are well corrected in a wide image circle region. Further, chromatic aberration is well corrected as well.

It is preferred that the conditions of equations (1) to (6) be satisfied in the present invention, and thus, correspondence is next described between each embodiment as described above and the conditions of equations. First, Table 5 to Table 8 each show the radius of curvature r of the concave, reflective mirror M_c, focal lengths f_i of the i-th converging groups G_i (i=1 to 3), Petzval sums p_i, apparent refractive indices n_i, image magnifications β_i a magnification β_{12} of a combinational system of the first converging group G_1 with the second converging group G_2, an image magnification β_3 of the third converging group G_3, a Petzval sum p of the total system and a magnification β of the total system in each embodiment as described above. Here, the total system is represented by G_T, and blocks for Petzval sum p_i and image magnification β_i corresponding to the total system G_T indicate the Petzval sum and image magnification of the total system, respectively.

TABLE 5

Specifications of first embodiment

	r	f_i	p_i	n_i	β_i	β_{ij}
G_1		−197.278	[illegible]	[illegible]	[illegible]	−0.32802
G_2	89.277	56.4287	−0.02674	−0.66288	−0.68461	
G_3		[illegible]	[illegible]	[illegible]	−0.76215	−0.76215
G_F			[illegible]	—	[illegible]	0.25004

TABLE 6

Specifications of second embodiment

	r	f_i	p_i	n_i	β_i	β_{ij}
G_1	—	−236.848	[illegible]	[illegible]	[illegible]	[illegible]
G_2	[illegible]	58.5864	[illegible]	[illegible]	[illegible]	
G_3	—	−2060.81	0.03442	−0.140978	−0.750195	−0.750195
G_F	—	—	[illegible]	—	[illegible]	0.24971

TABLE 7

Specifications of third embodiment

	r	f_i	p_i	n_i	β_i	β_{ij}
G_1	—	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
G_2	[illegible]	66.2828	[illegible]	[illegible]	−0.620527	
G_3	—	−696.956	0.03173	−0.045219	−0.75104	−0.75104
G_F	—	—	0.00029	—	0.25033	0.25033

TABLE 8

Specifications of fourth embodiment

	r	f_i	p_i	n_i	β_i	β_{ij}
G_1	—	−105.504	−0.01079	0.87843	0.46888	−0.39211
G_2	−92.7068	58.588	−0.02575	−0.66287	−0.83627	
G_3	—	−107.983	0.03733	−0.24808	−0.63959	−0.63959
G_F	—	—	0.00079	—	0.25079	0.25079

Further, based on Table 5 to Table 8, values are calculated for (P_1+P_3), P_2, $P_1+P_2+P_3$, β_{12}, β_3, and β in each embodiment, and the following Table 9 shows the calculated values.

TABLE 9

Table of correspondence conditions

Conditions / mbodiment	1	2	3	4
(1) [illegible]	[illegible]	[illegible]	[illegible]	[illegible]
(2) $p_2 < 0$	[illegible]	[illegible]	[illegible]	[illegible]
(3) $\lvert p_1 + p_2 + p_3 \rvert$ [illegible]	[illegible]	[illegible]	[illegible]	0.00079
(4) $0.1 < \lvert \beta_{12} \rvert < 0.5$	0.32802	0.33286	0.33331	0.39211
(5) $0.25 < \lvert \beta_3 \rvert < 2$	0.76215	0.7502195	0.75104	0.63959
(6) $0.1 < \lvert \beta \rvert < 0.5$	0.25004	0.24971	0.25033	0.25079

From this table, it is seen that either one of the above-described embodiments satisfies the conditions of equations (1) to (6).

The embodiments as described above employed quartz as a glass material for forming the refractive optical system, but another optical glass such as fluorite may be used.

Next, an embodiment of a common exposure apparatus using the catadioptric projection optical system **5** of the present invention. In this embodiment, as shown in FIG. **31**, the first converging group G_1 includes a reflector **14** changing a traveling direction of light that travels in the first converging group G_1. Therefore, the optical axis AX**1** of the first converting group G_1 is constituted by optical axes AX**1***a* and AX**1***b* as shown in FIG. **31**. The techniques relating to an exposure apparatus using a catadioptric projection optical system is described, for example, in Japanese Laid-Open Patent Application No. 5-72478, or the like.

Thus, the present invention is by no means limited to the above-described embodiments, but may employ a variety of constitutions within a range not departing from the essence of the present invention.

Since the catadioptric projection optical system of FIG. **2** is so arranged that the image is once formed between the concave, reflective mirror and the second plane (image plane), there are advantages that a compact prism type beam splitter can be used and that an optical path between the concave, reflective mirror and the image plane can be set long. Accordingly, deterioration may be reduced for image-

forming characteristics due to nonuniformity of characteristics in the semitransparent surface of beam splitter, and the working distance can be extended. In other words, the catadioptric projection optical system can secure a sufficiently long optical path to the wafer (image plane P**2**), of the illumination light reflected by the concave, reflective mirror M_2, because an intermediate image is formed between the mirror M_2 and the second image-forming optical system G_3. Therefore, a number of refractive lenses can be arranged in the optical path to achieve satisfactory image-forming performance. This also caused an effect that a distance between a wafer-side end face of refractive lens and the wafer, which is the working distance, was long enough.

Also, different from the ring field optical system for projecting only an annular part using an off-axis light beam, the optical system of the invention includes an advantage that it can employ the one-shot exposure method under a high numerical aperture.

Since an aperture stop can be placed in the second image-forming optical system, the optical system of the invention can enjoy an advantage that the a value being a coherence factor can be freely controlled.